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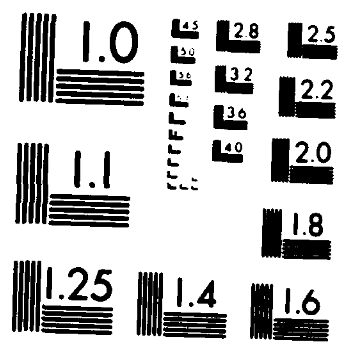
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The Effects of a D.C. Electric Field on the Current Driven Ion Cyclotron Instability

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We provide a nonlocal kinetic formalism ~~to~~ study the electrostatic ion waves that can be excited in a magnetised plasma including a d.c. electric field such as a double layer. The d.c. electric field can have components parallel ~~($E_{\parallel}$)~~ and perpendicular ~~($E_{\perp}$)~~ to the uniform ambient magnetic field. In a collisional plasma, $E_{\parallel}$ can give rise to a magnetic field aligned drift V_d, of the electrons with respect to the ions, while $E_{\perp}$ provides an $E_{\perp} X B$ drift to both the species. For $V_d = 0$, our formalism recovers the ion cyclotron-like modes ~~suggested by Ganguli et al.~~, while for $E_{\perp} = 0$, ~~we recover~~ the ion cyclotron modes ~~discussed by Drummond and Rosenbluth~~. ~~We study~~ the electrostatic ion modes for arbitrary values of V_d and $E_{\perp}$. It is found that the real frequency is strongly affected by the transverse component of the d.c. electric field and can assume values much different from the harmonics and may even get below the first harmonic. The growth rate is influenced by the field aligned electron drift.

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THE EFFECTS OF A D.C. ELECTRIC FIELD ON THE CURRENT DRIVEN ION CYCLOTRON INSTABILITY

INTRODUCTION

The presence of the magnetic field aligned electron drift can lead to the current driven ion cyclotron instability in collisionless[1] and collisional[2] plasmas. In a collisional plasma the field aligned electron drift V_d may be due to a field aligned component of a d.c. electric field. Recently, laboratory experiments[3,4] report ion-cyclotron-like waves associated with double layers in a magnetised plasma which can not be explained satisfactorily by the existing theories[1,2] of the ion cyclotron instabilities, since these theories do not include a transverse component of a d.c. electric field in their initial equilibrium. This is a crucial feature of a magnetised plasma containing a double layer. In order to study the role of the transverse component of a d.c. electric field in the generation of ion-cyclotron-like waves, Ganguli et al.[5,6] used a nonlocal kinetic theory and concluded that it is possible to excite electrostatic ion waves around the ion cyclotron frequency. These waves are driven by an inhomogeneity in the energy density of the ion cyclotron waves introduced by a localized $E_\perp$ X B drift. The theory was based on idealized conditions. Recently, a rigorous kinetic theory[7] has been developed which supports the earlier conclusions[5,6] and distinguishes the inhomogeneous energy density driven modes[5] from the Kelvin-Helmholtz modes. We have further generalised the kinetic theory[8] to include a magnetic field aligned electron drift V_d and the neutral-species collisions. In the limit where the transverse component of the electric field $E_\perp \to 0$, we recover the current driven ion cyclotron waves[1,2] and for $V_d \to 0$, we recover the waves described by Ganguli et al.[5-7]. Here we study the ion modes in the simultaneous presence of both the perpendicular component of a d.c. electric field and a magnetic field aligned electron drift.

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THEORY

The dispersion differential relation for the electrostic modes in a magnetised collisional plasma including a transverse component of a d.c. electric field and an equilibrium magnetic field aligned electron drift with respect to the ions, is given by[8],

$$A(\xi)\frac{d^2\Phi(\xi)}{d\xi^2} + Q(\xi)\Phi(\xi) = 0 \quad , \tag{1}$$

where $\xi = x/\rho_i$, $\rho_i = v_{ti}/\Omega_i$ is the ion gyroradius, $\Phi(\xi)$ is the perturbed electrostatic potential and,

$$A(\xi) = -\frac{1}{2}\left(C\sum_n \Gamma_n'(b)\zeta_i Z\left(\frac{\omega_1 + i\nu_i - n\Omega_i}{|k_{||}|v_i}\right) + \tau D\sum_n \Gamma_n'(b)\zeta_{i\nu} Z\left(\frac{\omega_1 + i\nu_i - n\Omega_i}{|k_{||}|v_i}\right)\right) \quad , \tag{2}$$

$$Q(\xi) = C\left(1 + \sum_n \Gamma_n(b)\zeta_i Z\left(\frac{\omega_1 + i\nu_i - n\Omega_i}{|k_{||}|v_i}\right)\right) + \tau D\left(1 + \sum_n \Gamma_n(b)\zeta_{i\nu} Z\left(\frac{\omega_1 + i\nu_i - n\Omega_i}{|k_{||}|v_i}\right)\right), \tag{3}$$

where $C = 1 + \zeta_{e\nu}Z(\zeta_e - \delta\bar{V}_d)$, $D = 1 + (\zeta_e - \delta\bar{V}_d)Z(\zeta_e - \delta\bar{V}_d)$, $\zeta_\alpha = (\omega_1 + i\nu_\alpha)/|k_{||}|v_\alpha$, $\omega_1 = \omega - k_y V_E(x)$, $V_E(x) = -cE_\perp(x)/B_0$, $\bar{V}_d = V_d/v_{ti}$, $\zeta_{\alpha\nu} = i\nu_\alpha/|k_{||}|v_\alpha$, $\Gamma_n(b) = \exp(-b)I_n(b)$, I_n are the modified Bessel functions, $b = (k_y\rho_i)^2/2$, $\Gamma'(b) = \partial\Gamma/\partial b$, α denotes the species, ν_α is the neutral-species collision frequency, $\tau = T_i/T_e$, $\mu = m_{ion}/m_{ele}$, $\delta = \sqrt{\tau/\mu}$ and $Z(\zeta)$ is the plasma dispersion function.

Briefly, the derivation of (1) can be understood if the dispersion relation (A1) of reference (9), for the collisional ion cyclotron waves, is considered. The transverse d.c. electric field provides a Doppler shift to

the frequency, ω. Therefore we replace ω by ω_1 in (A1) of reference (9). Since the d.c. electric field is nonuniform, we convert this algebraic dispersion relation to a nonlocal condition by replacing ik_x by the operator $\partial/\partial x$ and reduce it to a second order differential equation by expanding the Bessel functions to $O(\partial^2/\partial x^2)$. Only the n=0 harmonic for the electrons is retained.

If the transverse component of the d.c. electric field is chosen to be piecewise continuous, a nonlocal dispersion relation can be obtained[5-8],

$$- \kappa_I \, \mathrm{Tan}(\kappa_I/2\varepsilon) = i\kappa_{II} \quad , \tag{4}$$

where $\kappa_I{}^2=Q/A$, $\varepsilon=\rho_i/L$, L is the characteristic scale length associated with the transverse d.c. electric field and κ_{II} is identical to κ_I if $E_\perp=0$. We now proceed to find the eigenvalues of (4).

RESULTS AND DISCUSSION

When (4) is solved for $V_d=0$ and the species-neutral collisions are neglected, we recover the electrostatic ion waves discussed by Ganguli et al.[5-8]; while for $E_\perp=0$ we recover the ion cyclotron waves[1]. In figure (1) we choose b=0.475, $\tau=0.7$, $\varepsilon=0.1$, $\mu=29392$ (oxygen plasma), $u=k_{||}/k_y=0.09$, $\nu_i=\nu_e=0$ and $\bar{V}_d=25$. Initially, for $\bar{V}_E=V_E/v_{ti}=0$ we obtain a root for the current driven ion cyclotron wave[1]. As $\bar{V}_E$ is increased we find that the real frequency is significantly affected while the growth rate is only marginally increased. Thus, as $E_\perp$ is increased the character of the current driven ion cyclotron instability[1] changes. Conversely, when $E_\perp$ is held constant and V_d is increased the real frequency is marginally affected while the growth rate changes significantly. In either case, depending on

the values of V_d and $E_\perp$, the mode character differs from either the current driven or the inhomogeneous energy density driven ion cyclotron waves. This may explain the apparent discrepancy between the ion cyclotron modes as reported by Alport et al.[3] where $E_{||}/E_\perp > 1$ and V_d is significant and that of Sato et al.[4] where $E_{||}/E_\perp << 1$ and V_d is insignificant. More details will be discussed elsewhere.

In figure (2) we choose a set of parameters that are typical of the auroral ionosphere where ion-cyclotron-like waves are reported in conjunction with d.c. electric fields[10]. We use $\bar{V}_E = -0.5$, $\bar{V}_d = 30$ and 25, $\tau = 1$, $\mu = 29392$, $\varepsilon = 0.1$, $\nu_i/\Omega_i = 0.0333$, $\nu_e/\Omega_i = 12$, $u = 0.15$ and 0.17 and plot the growth rate γ/Ω_i and the real frequency ω_r/Ω_i as a function of b. Note that the above values of $\bar{V}_d$ are subcritical for the collisional ion cyclotron instability[2]. However, in the presence of $E_\perp$, the threshold for the ion cyclotron instability lowers and a coherent instability around the ion cyclotron frequency is possible. . The necessary condition for the ion cyclotron instability[1,2] is that $(\omega - k_{||}V_d) < 0$. For the values of V_d which are subcritical this condition can not be satisfied. The introduction of an $E_\perp$ initiates an $E_\perp$ X B drift which Doppler shifts the frequency, i.e., $\omega \to \omega_1 = \omega - k_y V_E$. Thus, in the region over which the $E_\perp$ is localized the necessary condition for the onset of the ion cyclotron instability becomes $(\omega_1 - k_y V_E) < 0$. Since ω_1 can be smaller than ω, it becomes easier to satisfy the necessary condition and thereby the threshold is effectively lowered. Further details will be provided elsewhere. It should be noted that in both the figures the transverse scale length associated with the field aligned drift L_c, is assumed to be of the same order as L.

CONCLUSIONS

In this short paper we have shown that in a magnetised collisional plasma, the presence of a d.c. electric field such as double layers or shocks, can give rise to electrostatic ion waves. In the limit where the perpendicular component of the d.c. electric field is zero the ion waves are identical to the ion cyclotron waves in a collisional plasma whereas in the limit where the magnetic field aligned electron drift is zero the ion waves are identical to the inhomogeneous energy density driven waves. For smoother transverse d.c. electric field profiles the differential equation (1) is solved numerically for the eigenvalues. Initial results indicate that there is little change in the eigenvalues when smoother electric field profiles are considered.

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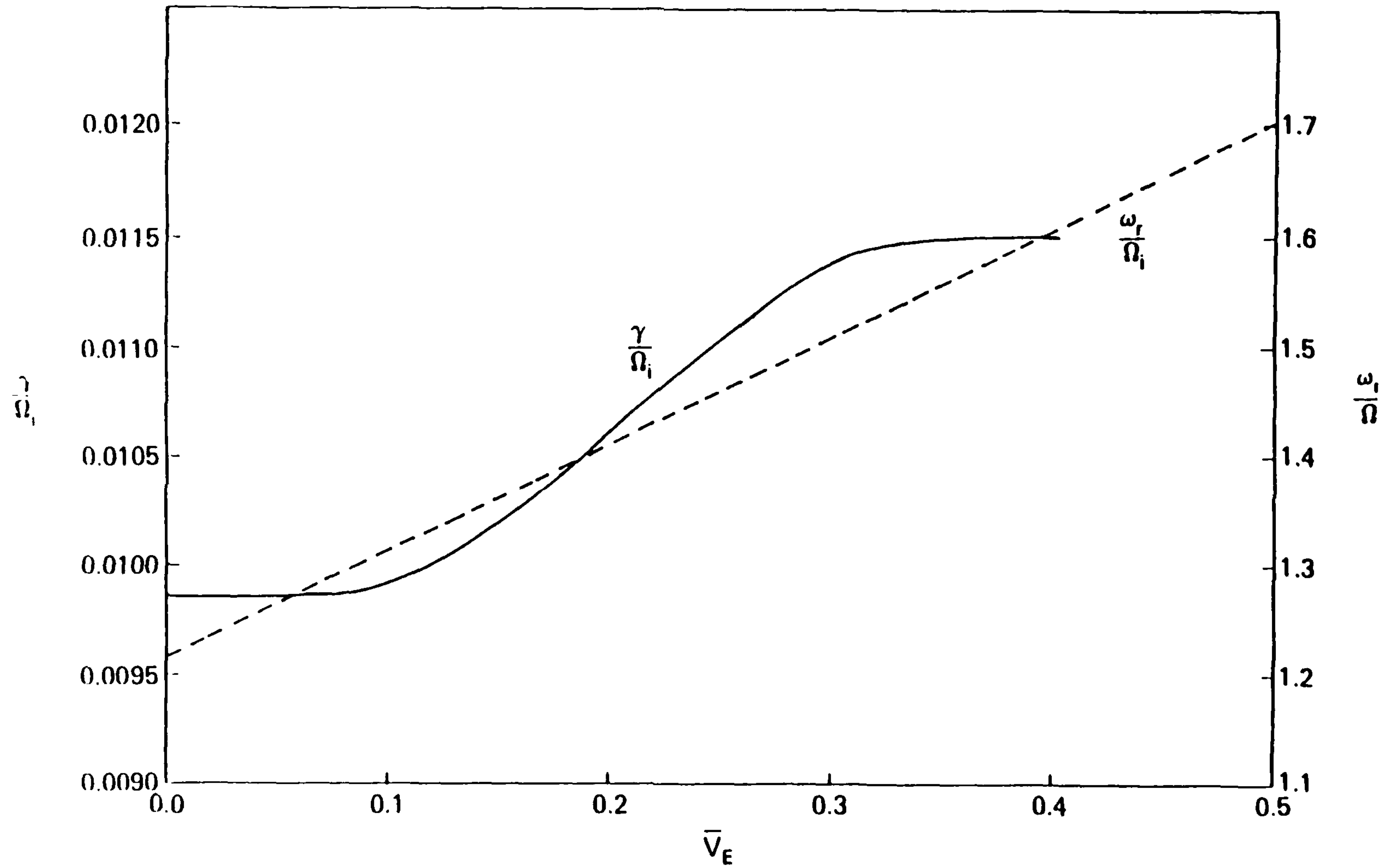

Fig (1) A plot of ω_r/Ω_i and γ/Ω_i against $\bar{V}_E$. Here b=0.475, τ=0.7, μ=29392, ε=0.1, $\bar{V}_d$=25 and $\nu_i=\nu_e=0$

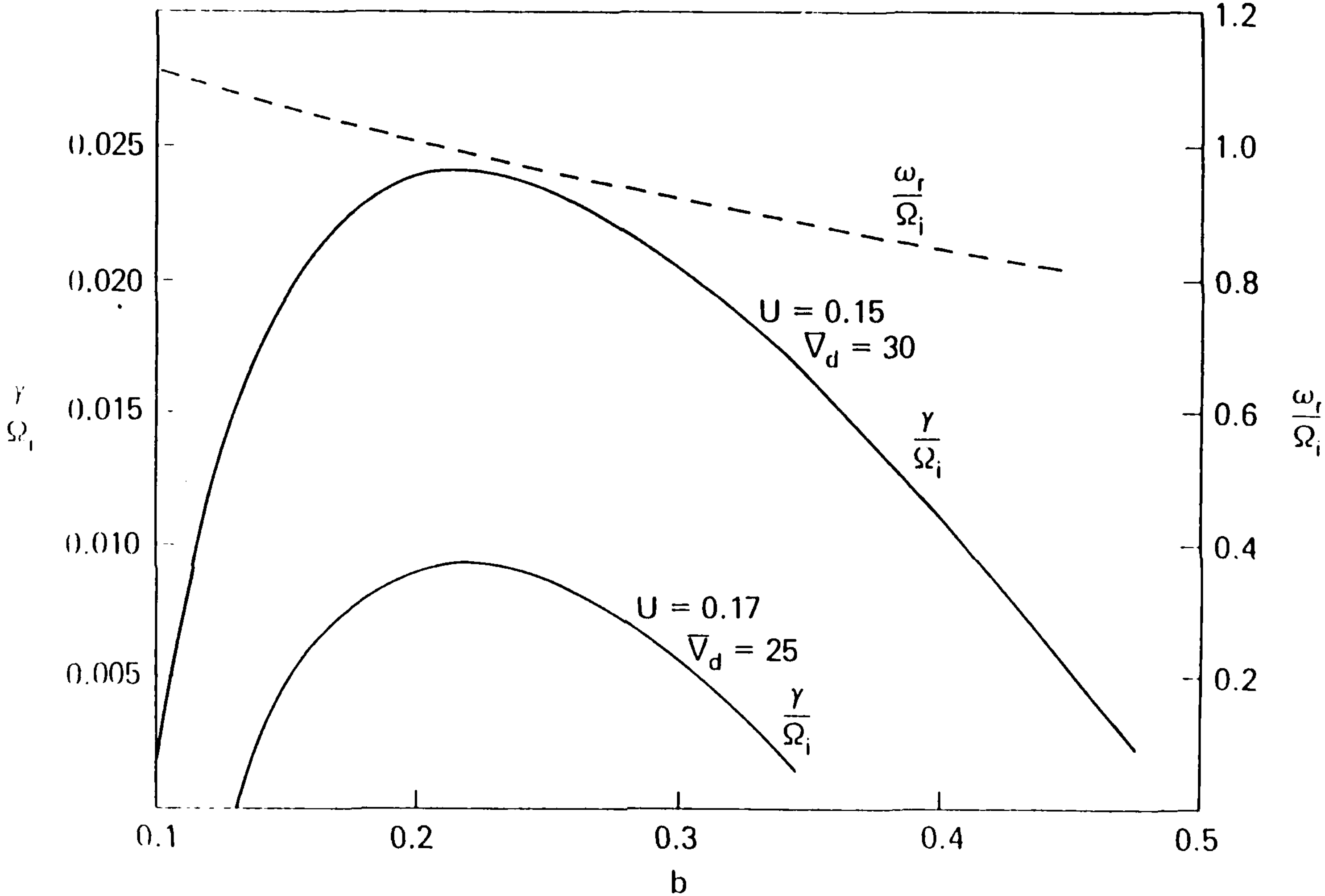

Fig (2) A plot of ω_r/Ω_i and γ/Ω_i against b. Here $\overline{V}_E=-0.5$, $\tau=1$, $\nu_i/\Omega_i=0.0333$, $\nu_e/\Omega_i=12$, $\overline{V}_d= 30$ and 25 and $u= 0.15$ and 0.17.

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